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Water and energy consumption of *Populus* spp. bioenergy systems: A case study in Southern Europe

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A B S T R A C T

With the objectives of climate change mitigation and energy independence, energy crops have been proposed as an alternative to fossil fuels. In recent years short rotation energy crops have been promoted because they provide biomass in short periods of time. However, the impacts of water consumption, in both the impact on the energy balance due to the consumption of irrigation as the impacts on existing water resources, have not been analyzed in depth. This study evaluates the relationship between water, energy and CO_2 emissions of a plot of *Populus* spp. in Spain with the aim of evaluating the feasibility of its implementation as large-scale cultivation. For the energy and environmental assessment it has been used the life cycle analysis methodology. The results show positive energy balance and environmental improvement respect other energies such as natural gas. Consumption of water required to avoid a kg of CO_2 is 4.6 m^3 and per unit of energy obtained is 45 $m^3\,GJ^{-1}$ considering a life cycle approach and in relation to the water availability of the basin could increase the pressure. Hence, in order to establish energy crops for climate change mitigation water consumption associated must be taken into account for future energy planning.

Contents

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1. Introduction

Biomass has received recent attention as a promising way to develop local and sustainable energy sources, able to reduce dependency on external sources and carbon emissions. In addition, biomass discussion is driven by rural development as it can promote job creation and improving competitiveness [1]. For this purpose, bioenergy is being promoted through several EU Directives [2,3] as well as national policies [4,5]. For biomass to play a significant role in the world's energy future, dedicated energy crops are essential and short rotation energy crops are gaining popularity internationally [6]. Forest crops in short rotation forestry (SRF) can produce biomass from fast-growing species in high densities and can be collected in short cycles. They have become important to provide raw material in relatively short periods of time and *Populus* spp. has been presented as one of the most promising in EU. This is due to its high yield and high ecological interest in terms of low input requirements and biodiversity maintenance compared with other extensive energy crops [7].

Recently more studies about the environmental performance of energy crops have been carried out in order to determine which is the real impact on the environment of energy crops cultivation [8–10]. Discussion about its sustainability has been focused on the analysis of land availability and uses and energy input–ouput yields [11–13]. Even the last European Directive [3] requires the analysis of the greenhouse gas emissions related to energy crop production and biodiversity impacts on the environment where they are cultivated [3]. However, neither energy balance nor water consumption has been required in the contents of the Directive [3].

There is a large uncertainty on the future impacts of climate change on water resources [14] and the IPCC report on climate change analyzes the potential impacts that climate change could have on the supply and demand of fresh water [15]. According to the regions, it is expected an increase or decrease in runoff that would mainly affect the availability of fresh water and water quality. In addition, a temperature increase would lead to increased evapotranspiration and crops would demand a higher irrigation although total precipitation was the same [15]. Nevertheless, the potential effects of the relationship between biomass energy and the associated water consumption have not been rigorously analyzed. Some studies have evaluated the water footprint and the potential impacts on water resources of biofuels [16,17]. It has been evaluated for several nations, the water footprint [18] of different primary energy carriers derived from biomass expressed as the amount of water consumed to produce a unit of energy ($m^3\ GJ^{-1}$).

However, the consumption of water resources in areas with significant water shortages, such as the South and the East of Spain, has not been taken into account [19]. Several researches on SRF management have been made in central Europe or North America [20–24] where water is not a limiting factor and plant spacing and cutting cycles are the most important agronomic aspects. For Mediterranean countries where water is a scarcity, data from long-term trials may offer additional information to better understand *Populus* spp. dynamics. For Spain, the virtual water content and waterfootprint of biofuel consumption has been analyzed [19] and also the water needs for energy production according to the energy sector and technology mix evolution planned for 2030 [25]. Nevertheless, the water consumption of SRF crops in Southern Europe has not yet been analyzed.

This paper evaluates the relationship between water and energy of the production of energy from a crop in SRF of *Populus* spp. located in Northeastern Spain. To do that, it is analyzed water consumption and its relation with water availability, energy consumption and environmental performance of this plantation. The plot has been divided in two densities in order to evaluate different crop managements regarding to water-energy consumption and environmental performance. The results are related to the Mediterranean area and the available resources. Nowadays, *Populus* spp. cultivation is traditional in the zone for wood purposes.

2. Materials and methods

Water consumption impact, energetic and environmental performance of *Populus* spp. in a SRF experimental plot has been analyzed during its first two years. Evapotranspiration, irrigation water and indirect water, associated to the production of agricultural machinery and agrochemicals, are calculated to obtain the total water consumption of *Populus* spp. crop. To complete energetic and environmental performance life cycle assessment (LCA) methodology has been used as in other studies of the research group where it has been analyzed the LCA of *Brassica carinata* cropping system in Southern Europe and the LCA of *Populus* spp. bioenergy system compared with *B. carinata* energy crop in local scenario [9,26]. Such method evaluates potential impacts throughout the life cycle of a product, process or activity, from the extraction of raw materials through production and use, to final disposal [27].

2.1. Site description, planting design and crop management

The experimental plantation is located in Girona, in Catalonia in Northeastern Spain, and it is irrigated with subterranean water from river Ter basin. It was established in February 2008 and is situated at 42°5′N and 3°3′E (Greenwich meridian). The mean annual temperature of the region is 14.5 °C [28] and the mean annual rainfall is about 5500 $m^3\ ha^{-1}$ (2700 $m^3\ ha^{-1}$ April–September) [28]. It has cultivated an area of 1 ha.

In order to optimize biomass production in a low input context a specific clone – named "Ballotino" has been chosen [29]. Such clone, created for biomass production application, is expected to produce high yields in short rotation systems, with a good quality of chips. The plot of 1 ha has been divided into two portions of 0.5 ha each one, the first planted with a low density (LD) of 6666 plants per ha (spacing 3 m × 0.5 m), and the other with high density (HD) of 20,000 plants per ha (spacing 1.65 m × 0.3 m). This design of the plot in two different densities has been made in order to analyze the energy consumption, irrigation and biomass production. The rotation for both scenarios is two years and the total duration of the plantation is 8–10 yr. Since there have been no fertilization stages before or after planting, the agricultural operations are limited to weed controls, herbicide, fungicide and insecticide treatments and irrigations.

2.2. Water consumption and availability methodology

It has been calculated the total water consumption of the crop from a life cycle approach, so the total water consumption has been defined as the sum of evapotranspiration and the indirect flows of water related to inputs invested in the crop.

Evapotranspiration is defined as the combination of two separate processes whereby water is lost on one hand from the soil surface by evaporation and on the other hand from the crop by transpiration [30].

$$\text{total water consumption}\,(\text{m}^3\,\text{ha}^{-1}) = \text{evapotranspiration} + \text{indirect water flows}$$

To contextualize the total water consumption results the water availability of Ter basin has been considered in relation with the current total water withdrawals. Total water withdrawal is defined as annual quantity of water withdrawn for agricultural, industrial and municipal purposes. It includes renewable freshwater resources as well as possible over abstraction of renewable groundwater or withdrawal of fossil groundwater and possible use of desalinated water or treated wastewater [31]. Water resources for Ter basin has been obtained by "WaterGap Model" [32] and water withdrawals have been obtained from The Catalan Water Agency (ACA) [33].

2.2.1. Evapotranspiration: precipitation and irrigation

The amount of water required to compensate the evapotranspiration loss from the cropped field is defined as crop water requirement. Although the values for crop evapotranspiration and crop water requirement are identical, crop water requirement refers to the amount of water that needs to be supplied, while crop evapotranspiration refers to the amount of water that is lost through evapotranspiration. The irrigation water requirement basically represents the difference between the crop water requirement and effective precipitation [30].

It is assumed that irrigation supplied to crop is exactly the part to complement water provided by precipitation. For irrigation, experimental data has been collected throughout the first 2 years until its first harvest.

To calculate evapotranspiration it has been apply the following equation [30]:

$$\text{ET}_\text{c}(\text{m}^3\,\text{ha}^{-1}\,\text{yr}^{-1}) = \text{ET}_0 K_\text{c}$$

The crop evapotranspiration under standard conditions, denoted as ET_c, is the crop evapotranspiration from disease-free, grown in large fields, under optimum soil water conditions, and achieving full production under the given climatic conditions [30]. It is assumed as the total consumption of the crop expressed as $\text{m}^3\,\text{ha}^{-1}\,\text{yr}^{-1}$. The evapotranspiration rate from a reference surface, not short of water, is called "reference evapotranspiration" and is denoted as ET_0. The K_c factor serves as an aggregation of the physical and physiological differences between crops and the reference definition [30].

The value for ET_0 has been obtained from the meteorological experimental station of "*Institut de Recerca i Tecnologia Agroalimentàries*" (IRTA-Mas Badia) [34] and K_c values have been obtained from experimental data of the zone. Table 1 shows the results of ET_0 and K_c.

2.2.2. Indirect water consumption

Indirect water consumption is the water flows consumed and associated to life cycle of inputs invested in the crop, such as: machinery, pesticides, irrigation infrastructures and diesel. Data for the calculation of indirect water consumption flows has been taken by the Ecoinvent Database [35].

Table 1
Monthly values of K_c and ET_0 used for the calculation of water evapotranspiration [34].

	ET_0 1st year ($\text{m}^3\,\text{ha}^{-1}$)	ET_0 2nd year ($\text{m}^3\,\text{ha}^{-1}$)	K_c
January	222.0	255.0	0.00
February	357.0	358.0	0.00
March	637.0	685.0	0.00
April	972.0	843.0	0.35
May	1183.0	1178.0	0.70
June	1400.0	1379.0	1.05
July	1600.0	1462.0	1.05
August	1195.0	1125.0	1.05
September	761.0	984.0	0.50
October	525.0	539.0	0.35
November	315.0	386.0	0.00
December	265.0	248.0	0.00

2.3. LCA of Populus spp. bioenergy system

The methodology selected to perform the global environmental analysis was LCA. This environmental tool follows ISO 14040 [27] guidelines, according to which LCA is divided into four steps: (1) goal and scope definition, (2) inventory analysis, (3) impact assessment, (4) interpretation. The environmental analysis was performed using the software program SimaPro 7.1.8 by Pré Consultants.

2.3.1. Functional unit

The functional unit is an outstanding measure, very defined and strict of the function that the system offers, being also the base on which the LCA must be carried out. In this study it has been selected two functional units. The first one is the cultivation of 1 ha of *Populus* spp. destined to produce biomass throughout the entire production cycle. This functional unit to cultivate 1 ha has been applied to both scenarios of high and low planting density. Moreover, the functional unit of 1 GJ stored in the crop has been also applied in order to compare energy systems.

2.3.2. System description

As shown in Fig. 1, the system under study includes all stages of agricultural production for the first cycle of the crop. Work in the plantation, production of herbicides, fungicides and insecticides, tractor and agricultural utensils manufacture and transport to the plantation for cultural operations are included. Energy is consumed and emissions are released in tractor operations in each field activity.

2.3.3. Life cycle inventory/quality of data

Biomass production was obtained using experimental data from IRTA-Mas Badia. The data used for the LCA were collected and classified during the establishment and the harvest of the crop such as agrochemical application doses ($\text{kg}\,\text{ha}^{-1}\,\text{yr}^{-1}$), type of machinery used, diesel fuel consumption ($\text{l}\,\text{ha}^{-1}\,\text{yr}^{-1}$), operating rate ($\text{h}\,\text{ha}^{-1}\,\text{yr}^{-1}$) and consumption of water ($\text{m}^3\,\text{ha}^{-1}$). Table 2 shows the life cycle inventory.

Production inventories of inputs, such as herbicides, tractors, utensils as well as data related to the life cycle of the fuel (production, distribution and consumption), were taken by literature [36,37] and the Ecoinvent Database [35]. The characterization of the heating value of *Populus* spp. biomass was obtained from previous studies where it has been analyzed the LCA of *Populus* spp. comparing with *B. carinata* and gas natural [9].

In reference to the natural gas system, the data used was obtained directly from the ETH-ESU 96 database, the inventory considered was specifically natural gas HP user in Spain, which considers all the life cycle stages until the delivery of this fuel to a regional Spanish power plant [38]. The assumed origins of imported

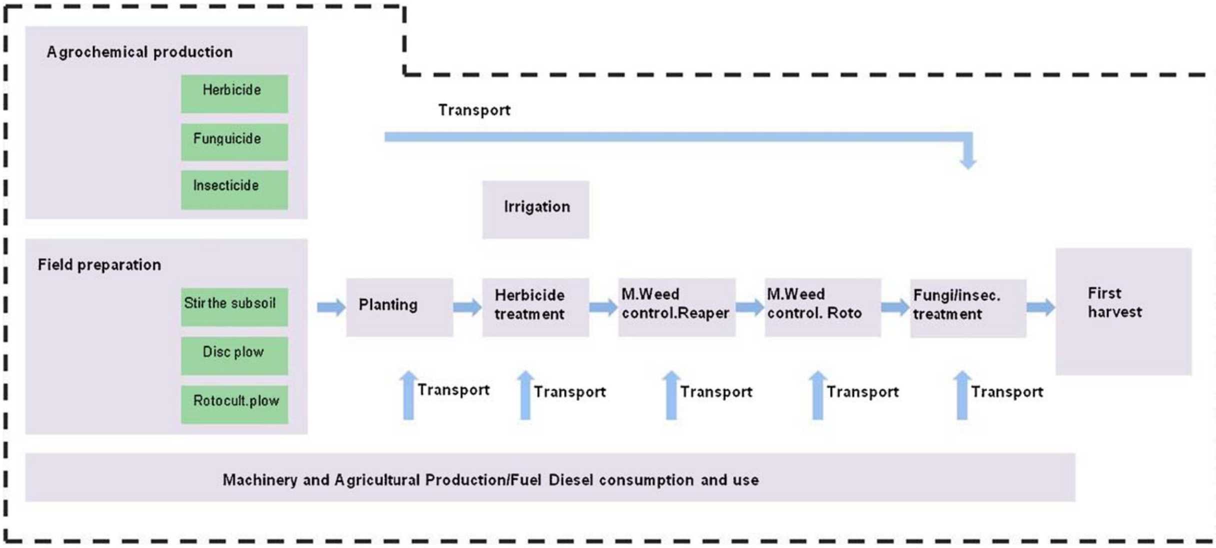

Fig. 1. First cycle of *Populus* spp. system boundary.

natural gas are Algeria (78%), Norway (13.8%) and the importation mix of Union for the Coordination of Production and Transmission of Electricity is 8.20% [38].

2.3.4. Energy assessment

Energy inputs were calculated by "Cumulative Energy Demand v 1.4" [38,39] using Simapro 7.1.8, while the energy outputs were determined by multiplying the dry matter yields obtained by the low heating value of the *Populus* spp. (18.20 MJ kg^{-1}) taken from experimental data [9]. This value was obtained by combusting 1 g sample in a LECO AC-300 calorimeter to determine the gross calorific value (norm ASTME 711-87 "Gross calorific value of refuse derived fuel by bomb calorimeter"). All energy balances are referred to the output that expresses the calorific value contained in the biomass, excluding the stage of conversion of biomass to heat and or electricity.

In addition, it has been determined the efficiency of the crop energy production, calculated as a ratio between energy output and energy input, and the net energy yield calculated as the difference between energy output and energy input.

2.3.5. Life cycle impact assessment (LCIA) methodology

SimaPro 7.1.8 software was used for the environmental evaluation. The impact categories included are: abiotic depletion (AD kg Sb equiv.); acidification (A kg SO_2 equiv.), eutrophication (E kg PO_4 equiv.), global warming potential (GWP kg CO_2 equiv.); ozone layer depletion (ODP mg CFC-11 equiv.); human toxicity (HT kg 1,4-DB equiv.); fresh water aquatic ecotoxicity (FWAE kg 1,4-DB equiv.); marine aquatic ecotoxicity (MAE T 1,4-DB equiv.); terrestrial ecotoxicity (TE kg 1,4-DB equiv.) and photochemical oxidation (PO kg C_2H_4 equiv.).

Table 2
Life cycle Inventory of the first cycle of the crop.

Operation	Tractor		Implement			Diesel consumption ($l\,ha^{-1}\,yr^{-1}$)	Input rates
	Weight (Mg)	Power (kW)	Tool	Weight (kg)	Operating rate ($h\,ha^{-1}\,yr^{-1}$)		
Stir the subsoil	2.80	63	Subsoiler	640	6.75	50.5	–
Plow	2.97	37.5	Plow	375	7.00	40.0	–
	2.97	37.5	11 disc plow	1650	4.17	20.0	–
	2.97	37.5	Rotocultivator	410	4.25	32.0	–
Herbicide treatment	2.97	37.5	Boom sprayer	300	1.50	10.0	5 $l\,ha^{-1}$ oxyfluorfen
Water irrigation	–	–	Pump	96	74.38	165.5	10190.7 $m^3\,ha^{-1}$ $2yrs^{-1}$
Plantation							
Low density	4.167	75	Rototille	800	8.20	16.3	6666 plants ha^{-1}
High density	4.167	75	Rototille	800	18.64	32.0	20,000 plants ha^{-1}
Mechanical weed control to reap							
Low density	2.80	63	Reaper	470	4.67	21.0	–
High density	0.358	13.5	Reaper	358	11.0	6.5	–
Mechanical weed control							
Low density	2.97	37.5	Rotocultivator	410	3.00	7.0	–
High density	0.88	13.5	Rotocultivator	120	6.00	6.8	–
Fungui and insecticide treatment							
Low density	2.70	63	Boomsprayer	620	1.17	10.5	0.18 kg ha^{-1}(10% A), 2.35 kg ha^{-1} (B)
High density	77.15	97.5	Boomsprayer	620	3.00	22.0	0.6 kg ha^{-1} (10% A), 2.5 kg ha^{-1} (B)
Harvest							
Low density	10.36/11.58	232.5/412.5	Harvester	500	0.62	34.05	–
High density	10.36/11.58	232.5/412.5	Harvester	500	0.88	47.35	–

A: 10% cyproconazole, B: 75% chlorpyrifos, C: 25% chlorpyrifos.

Table 3
Water consumption of life cycle *Populus* spp. stages in years 2008 and 2009.

	$m^3\ ha^{-1}\ 2yr^{-1}$		$m^3\ GJ^{-1}\ 2yr^{-1}$	
	Low density	High density	Low density	High density
Evapotranspiration (A)	12,101	12,101	41.4	34.5
Indirect water (B)				
Agricultural machinery production	619.6	1014.5	2.1	0.2
Agrochemical production	48.8	537.8	0.2	1.5
Diesel	23.2	41.4	0.1	0.1
Total water consumption	691.7	1593.7	2.4	4.5
Total water consumption (A + B)	12792.7	13694.7	43.8	46.0

The impact category GWP has been analyzed more thoroughly but similar analyses could be done for all the analyzed impact categories. Optional phases of normalization and weighting are excluded in order to avoid subjectivity in the analysis. The score for this impact category would be assigned by multiplying the amount of substance emitted by the corresponding characterization factor [37].

3. Results and discussion

3.1. Water analysis of Populus spp. bioenergy crop

3.1.1. Water consumption: evapotranspiration and indirect water

Populus spp. is characterized by its strong higrofilia and so regular irrigations are necessary more in weather conditions. In Mediterranean climate condition the precipitation is not evenly distributed over the year, summer months are dry, so that crops suffer from water shortage in this period and irrigation is required to maintain potential growth. The amount of water depends on the environment, the reserve of water in the soil and on irrigation system efficiency [40]. In the experimental plantation irrigation has been carried out during the summer months (April–September) for two years. It has been used a drip irrigation system with emitters located every 0.3 m for both densities. This system allows the optimum use of water.

The calculated evapotranspiration, called A in Table 3, for 2 years of *Populus* spp. cultivation is 6137 $m^3\ ha^{-1}\ yr^{-1}$ for the first year and 5965 $m^3\ ha^{-1}\ yr^{-1}$ for the second year, with a total consumption of 12,101 $m^3\ ha^{-1}\ 2\ yr^{-1}$. The result is equal for both densities because the applied formula does not add terms for different crops densities.

It has been estimated water consumption associated with the production of agricultural machinery, agrochemicals production and distribution of diesel. The results obtained are also shown in Table 3 as B. The most contribution of the indirect water is due to agricultural machinery production for low and high density; follow by agrochemical production in high density due to an increased application of insecticide.

The consumption of irrigated water is shown in Table 4. These results of irrigation are within the range indicated by other authors for different areas of Spain: 2000–6000 $m^3\ ha^{-1}\ yr^{-1}$ [41], and below irrigation values of other traditional crops in the zone such as corn 5000–7000 $m^3\ ha^{-1}\ yr^{-1}$ [42,43].

Table 4
Water irrigation of life cycle *Populus* spp. stages in years 2008 and 2009.

	$m^3\ ha^{-1}$		$m^3\ GJ^{-1}$	
	Low density	High density	Low density	High density
1st year	1389.9	2527.1	4.8	7.2
2nd year	2226.1	4047.6	7.6	11.5
Total	3616.1	6574.7	12.4	18.7

In relation with total water consumption; 28.3% of this consumption is due to water irrigation for low density scenario. In high density scenario, this percentage is 48.0%.

3.1.2. Water availability

With the aim of determining the current pression of TER basin it has been calculated the ratio between water availability and water withdrawals for human consumption, industrial and agriculture. Long term potential water availability of Ter basin, calculated considering 1961–1990 climate series, is 95.13 $hm^3\ yr^{-1}$ [32]. In the area of the experimental plot water availability is 73.2 $hm^3\ yr^{-1}$ and the water withdrawal is 25.2 $hm^3\ yr^{-1}$:14.0 $hm^3\ yr^{-1}$ for human consumption, 9.8 $hm^3\ yr^{-1}$ for agriculture and 1.4 $hm^3\ yr^{-1}$ for industrial use [33]. The ratio of water withdrawal and water availability is 34.4%. Ratios above 25% would be found within the area of water stress [44]. The values for Italy and France [44] are similar to our results.

Nowadays, *Populus* spp. cultivation traditional in the zone for wood purposes is in decline so there will be land available for cultivation or for urban construction. According to the obtained results the implementation of SRF plantations in a large-scale would be in current areas where *Populus* spp. is cultivated for wood production, in other case this would involve the increas of consumption of irrigation water modifying the demand of water in the area. However, the water needed for growing a *Populus* SRF crop is lower than the consumption of other irrigated crops, as corn, that can compete for the same lands in Mediterranean area.

The implementation of long-term and/or large-scale planting should be adapted to the structure of water supply of various existing economic activities and planned for the future, and to the system's ability to cope with water shortages.

3.2. Energy analysis of Populus spp. energy crop

3.2.1. Energy input

The total energy consumed during the first cycle of the plantation is 31.12 $GJ\ ha^{-1}$ and 46.67 $GJ\ ha^{-1}$ for low and high density, respectively. Energy consumption for diesel irrigation in both scenarios has been 11.55 $GJ\ ha^{-1}$ and 20.52 $GJ\ ha^{-1}$. Differences between them are due to a higher work of machinery in high density because of the space and number of trees that result in more diesel and time consumption used for the operation.

It is worth to notice that there are not many information in literature on energy consumption by irrigation because most experimental studies have been conducted in areas where irrigation was not necessary. The results are coherent with those published for a *Populus* spp. crop in Portugal where energy consumption of irrigation was 7.7 $MJ\ m^{-3}$ [45] that would represent 27.84 $GJ\ ha^{-1}$ for low density and 50.63 $GJ\ ha^{-1}$ for high density; and with the values of 21.5 $GJ\ ha^{-1}$ and 5.6 $GJ\ ha^{-1}$ recorded in perennial crops of a semi-arid Mediterranean environment [46]. For United States [47] it is estimated that 15% of the total energy expended for all crop production is used for pump irrigation water.

Table 5
Energy balance of the *Populus* spp. bioenergy system for two year.

	GJ ha^{-1}		
	Low density system	High density system	Gas natural system
Energy input (A)	31.1	46.7	53.5
Energy output (B)	292.1	351.1	292.1
Balance (B – A)	261.0	304.4	238.7
Efficiency (B/A)	9.4	7.5	5.5

Harvest has an energy consumption of 4.06 GJ ha^{-1} and 5.66 GJ ha^{-1} for low and high density, respectively. Planting has similar energy consumptions: 2.55 GJ ha^{-1} for low density 5.30 GJ ha^{-1} for high density. It represents 8.19% for the scenario of low density and 11.37% for high-density scenario. They agree with the values recorded for this operation around 4 GJ ha^{-1} [22]. Weed control is higher in low density due to the machinery used and a longer work. The energy consumption is 3.20 GJ ha^{-1} and 2.29 4 GJ ha^{-1}, respectively.

3.2.2. Energy output

The biomass production of SRF plantations of *Populus* spp. is highly variable in literature and there is a wide range of results [48–53]. This variability mainly depends on site characteristics (climate and soil for instance), but also on different techniques adopted, such clone, spacing and tending operations. For these reasons, it is difficult to compare values from different studies, as local conditions and crop management are heterogeneous. This said, as a tentative data, results of biomass production are generally included in a range between 10 and 15 t dry matter ha^{-1} yr^{-1} [22,49].

Biomass production obtained in our plot is 8.02 t dry matter ha^{-1} yr^{-1} for low density and 9.64 t dry matter ha^{-1} yr^{-1} for high density. It is straightforward to observe that these values are below average productions but this may be due to a low input design that means that it has not been used fertilizers. Moreover, the dynamics of biomass production over 11 years indicate that biomass values increase with rotation years, but this rise became less pronounced with increasing number of rotations [50].

3.2.3. Energy balance

The energy balance of the first two years, obtained for both scenarios, are shown in Table 5 together with efficiency defined as the ratio of energy produced and energy consumed.

The balance result obtained is higher than those published of 173–259 GJ ha^{-1} for three years cycle [54]. Energy balances ratios highlighted differences between silvilcultural treatments and machines or materials used [55]. In reference to the efficiency, the results of SRF plantations of *Populus* spp. is usually between 7 and 10 times the energy needed to produce these plantations [56]. Low-density scenario yields give better results in this sense.

If the low density system is taken as a reference to compare with the natural gas system, in order to achieve 292.1 GJ the energy required is 53.5 GJ. This results in a balance for natural gas of 238.7 GJ ha^{-1} and an efficiency of 5.5, both present in Table 5. The efficiency and balance of the low density system is relatively high compared to the high density system and the natural gas system. These results are consistent with those obtained in other studies of SosteniPrA research group [9].

3.3. Environmental analysis of Populus spp. energy crop

3.3.1. Total environmental impacts

The environmental impact of the *Populus* spp. energy crop for its first cycle is shown in Table 6. The overall results show that in all impact categories the values obtained in different equivalent units are higher for high density scenario than for low density scenario. Evaluation has been focused on the category of GWP because energy crops have been promoted in part because of the potential to mitigate CO_2 emissions [52].

Table 6
Environmental impacts of the first two years of a *Populus* spp. crop.

	Equivalent unit ha^{-1}		Equivalent unit GJ^{-1}	
	Low density	High density	Low density	High density
A.D (kg Sb equiv.)	12.43	17.98	0.043	0.051
A (kg SO_2 equiv.)	13.73	19.64	0.047	0.056
E (kg PO_4 equiv.)	3.03	4.31	0.010	0.012
GWP (kg CO_2 equiv.)	1888.19	2711.94	6.464	7.724
ODP (mg CFC-11 equiv.)	0.28	0.38	0.001	0.001
HT (kg 1,4-DB equiv.)	3234.51	6263.76	11.073	17.840
FWAE (kg 1,4-DB equiv.)	176.02	253.61	0.603	0.722
MAE (mg 1,4-DB equiv.)	149.70	221.46	0.512	0.631
TE (kg 1,4-DB equiv.)	59.28	84.81	0.203	0.242
PO (kg C_2H_4 equiv.)	0.28	0.41	0.001	0.001

The results show values of 1.89 Mg equiv. CO_2 ha^{-1} and 2.71 Mg equiv. CO_2 ha^{-1} in the first cycle. In the case of low density, the 42.54% is due to irrigation including emissions resulting from the life cycle of the diesel consumption in pumps. For the high density this percentage is 52.63%. These results are within the values recorded in other studies for the LCA of *Populus* spp. and *B. carinata* in Southern Europe and in a local scenario [9].

3.4. Relationship between water, energy and CO_2 emissions

Energy crops have been promoted for their potential to mitigate climate change, so to assess the reduction of CO_2 emissions it has been compared the results obtained with CO_2 emissions of natural gas to produce the same quantity of energy. The values obtained are shown in Table 7 and the water needed for avoiding kg of CO_2 equiv. and generating renewable energy (GJ) is showed in Table 7 as well.

The reduction of CO_2 emissions respect gas natural is 9.60 kg CO_2 equiv. GJ^{-1} and 8.34 kg CO_2 equiv. GJ^{-1} for low and high density, respectively.

The water needed for avoid 1 kg of CO_2 equiv. for both scenarios is almost the same. As it is expected that biomass values increase with rotation years [50], it is expected that the need of water consumption would be lower in next cycles. The needed of water per unit of energy for the *Populus* spp. experimental plot, considering the sum of evapotranspiration and indirect water flows, are considerable higher than for gas natural. These values are within the range of those presented for United States, 42 m^3 H_2O GJ^{-1}, or Brazil with 55 m^3 H_2O GJ^{-1} [18] for *Populus* spp. crops. Nevertheless they are over the results of 22 m^3 H_2O GJ^{-1} given for The Netherlands. In comparison with gas natural this ratio is considerably lower with a value of 4.9 m^3 H_2O GJ^{-1}. In other studies the values given for the gas natural has been even lower: 0.1 m^3 H_2O GJ^{-1} [18]. For others non-renewable energies, such as nuclear or coal, it have been calculated 0.1 m^3 GJ^{-1} and 0.2 m^3 GJ^{-1}, respectively. For solar energy the calculation of this value has been 0.3 m^3 GJ^{-1} [18].

Table 7
Values of CO_2 equiv. emissions and m^3 H_2O per GJ; and relation between m^3 H_2O and CO_2 equiv. emitted for *Populus* spp. in a low density and high density plantation and natural gas producing the same quantity of energy.

Units	Low density	High density	Gas natural
kg CO_2 GJ^{-1}	6.46	7.72	16.06
m^3 H_2O kg CO_2 $^{-1}$ avoided	4.56	4.68	–
m^3 H_2O GJ^{-1}	43.8	46.0	4.90

Populus spp. cultivation for energy production, in a Mediterranean climate, is a good alternative for decrease CO_2 emissions. Furthermore, a low density system is presented as a better option than high density system. Although energy production is higher in high density scenario the environmental impacts associated are also higher than for low density scenario. However in the sense of water consumption in a life cycle view, in comparing with gas natural the results show that *Populus* spp. crops are not as efficient. Nevertheless, as it is said above 28% and 48% of this water consumption correspond to water irrigation.

The decision to cultivate crops to biomass production with the aim of energy independence and climate change mitigation should take into account water consumption, mainly due to irrigation, and its effect on water availability in the area.

4. Conclusions

The results show that water consumption due to the introduction of irrigated crops in the area occupying new lands might increase the pressure already exerted on the system. It must also be taken into account that the most important extraction is for drinking water. On the other hand, *Populus* spp. cultivation for energy production purposes can be understood as an alternative to maintenance of this crop and avoiding its substitution for other crops or urbanization. According to the calculations, the first cycle of a *Populus* spp. bioenergy system cultivated in Southern Europe showed a positive energy balance characterized by high energy efficiency. Furthermore, the low density planting showed better results, both for energy and environmental aspects, if compared to high density planting. The higher production in high density system does not justify the major environmental impacts that are generated. Moreover, even lead to a major land use, that it is a resource constraint, it generates more impacts and over water consumption.

The relationship between water and energy is key in planning energy and water policies in the future. Climatic change and the need for energy independence from fossil fuels has led to the implementation and use of renewable energy. The results for the interrelation between water, energy and CO_2 emissions expose this dichotomy that arises before these crops. While for the mitigation of climate change is an effective and viable energy source compared to fossil energies, the associated water consumption is far from being efficient compared with non-renewable energies.

The bioenergetic system of *Populus* spp. in Southern Europe, as a new crop occupying new lands, should be restricted to areas where water availability is abundant and its consumption will not increase the water pressure in the area in current and future terms. In any case to supply a power plant, biomass *Populus* spp. energy crops should be applied as complement of other types of biomass such as forest residues, agricultural residues, etc. The search for alternative water sources such as the reuse of urban or industrial water for irrigation could be a possibility to asess.

These results and conclusions should be extended with the values obtained for the entire plantation, including processing energy. More research in needed however to investigate whether different *Populus* spp and SRF crop managements can influence in the economic feasibility of these crops compared with alternative land and water uses.

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